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PROBLEMS IN PETROLOGY.

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The development of the science of petrology from that condition of the study of rocks, properly termed petrography, is characterized by the shifting of the emphasis from the purely observational and descriptive phases of the work to those that relate to the origin and formation of rocks, both with respect to their occurrence as integral parts of the earth, and to their composition and structure.

Not that there is less need than formerly for accurate observation and study of rocks, and for thorough description of their composition, texture and occurrence, but the introduction of greater definiteness into conceptions of their modes of formation, and the widening of the horizon of this field of research through the experimental and synthetic investigations of the geophysicist, have advanced the study of rocks from the accumulation of data and statistics, to the formation of laws and relationships, both as regards minutest details of composition and texture, and with respect to petrographical provinces, and their connection with the dynamical history of the regions of the earth in which they occur.

As a consequence of this advance new problems present themselves, and invite the coöperation of workers in several branches of inorganic science. Leaving out of consideration for the present the great problems of metamorphism, some of which are being successfully treated by Adams, or have been under investigation by Van Hise and Leith, I wish to call your attention to certain phases of the study of igneous rocks that may be grouped under three heads for present purposes, as follows: (1) The actual mineral composition of igneous rocks, (2) the mathematics of the petrology of igneous rocks, and (3) petrographical provinces.

I. ACTUAL MINERAL COMPOSITION OF IGNEOUS ROCKS.

Although the minerals constituting various rocks are their most obvious features, aside from their general color and texture, and have been the chief object of study by petrographers since the introduction of microscopical methods of investigation, they still remain among the most important problems before the petrologist.

The exact composition, crystal characters and optical properties of many of the minerals are well known. But some of the commonest, such as the micas, amphiboles and aluminous pyroxenes, are not perfectly understood chemically, and the relation between their composition and optical constants is not so definite that one may be employed to determine the other, as is the case with the lime-soda-feldspars.

Moreover, the exact amounts of the component minerals in various kinds of igneous rocks have not been determined, except in a very few instances; nor has the precise composition of those minerals that occur in mixed crystals, that is, the principal ferromagnesian minerals, been determined in the vast majority of the rocks described.

There is, therefore, a great field of research, imperfectly cultivated, capable of yielding immediate returns of the first importance for the solution of other problems connected with the mineral composition of these rocks.

Similarly, more definite and specific study and description are needed of the crystal forms and arrangements of the mineral constituents of igneous rocks than have heretofore appeared in petrography, in order that the texture of various rocks may be clearly understood, since texture is a very definite exponent of physical conditions that attended the crystallization of each igneous magma. Up to the present time petrographers have been content with very vague and incomplete descriptions of rock textures, as well as of kinds and amounts of minerals composing various igneous rocks.

The determination of the kinds and amounts of the minerals in every rock leads to the problem of the formation of the minerals in each instance, and a comparison of the mineral composition of a rock with the chemical composition of the magma from which it

solidified. This involves the chemistry of solutions of inorganic compounds, chiefly silicates; the mutual interaction of the various chemical elements that appear in an analysis of the whole rock; together with the possible catalytic action of constituents, notably water gas, that may not become parts of the fixed compounds, but may escape in greater part upon the solidification of the magma.

Some of the minor problems, or factors, within this large one may be alluded to briefly as follows: The first and most obvious result of a strict correlation of the mineral composition of rocks with the chemical composition of the whole mass, representing the fixed components of the formerly liquid magma, is the recognition of the nonappearance in certain kinds of rocks of some minerals whose presence is necessary to satisfy the chemical requirements of the magma solutions. This is the case with completely crystallized but exceedingly fine-grained lavas of particular compositions, notably andesites.

Minerals that should be present to the extent of as much as 30 per cent. in some instances are not visible, are occult, and must

TABLE I.

	1.		2.	3.
SiO ₂	59.87	quartz	13.02	18.29
Al ₂ O ₃	15.02	orthoclase	17.24	9.46
Fe ₂ O ₃	2.58	albite	28.56	24.63
FeO	3.40	anorthite	17.28	14.18
MgO	4.06	diopside	3.99	—
CaO	4.79	hypersthene	11.11	—
Na ₂ O	3.39	hornblende	—	15.39
K ₂ O	2.93	biotite	—	14.38
H ₂ O	1.86	hematite	—	1.12
TiO ₂	0.72	magnetite	3.71	—
P ₂ O ₅	0.26	ilmenite	1.37	—
F	0.02	apatite	0.50	0.50
Etc.	1.10	water	1.51	0.84
	1.00.00	Etc.	1.26	1.26
			99.51	100.05

be hidden within the substance of those minerals that are visible; that is, they must be held in solid solution within other kinds of crystals. An example will illustrate the case.

A magma whose chemical composition is shown by analysis 1,

Table I., under favorable conditions should form the mineral compounds in the proportions shown in column 2. In this there are 13 per cent. of quartz, and 17 per cent. of orthoclase, together making 30 per cent. of the whole. And this amount of quartz is the least amount of free silica capable of separating from a solution of such a chemical composition, assuming that the minerals formed are those known to occur in igneous rocks. A magma of this chemical composition commonly crystallizes as a pyroxene-andesite composed, so far as the microscope can determine, of lime-soda-feldspar, pyroxene, and magnetite, with no visible quartz or orthoclase. And, yet, from the chemical analysis of the rock there should be 30 per cent. of these compounds.

The orthoclase molecules may be readily imagined in solid solutions within the lime-soda-feldspars, although in coarsely crystallized forms of such a magma, diorite, orthoclase crystals appear as independent individuals. It has been shown in the Geophysical Laboratory of the Carnegie Institution. that orthoclase and anorthite molecules form homogeneous mixed crystals when melted together and cooled in an open crucible. The disappearance of 17 per cent. of orthoclase in this particular andesite is, therefore, due to the conditions of solidification of the rock. The non-appearance of the quartz may be explained in part by its existence in solid solution in other minerals of which, however, we have not sufficient evidence at present; or it may occur in minute crystals mistaken for andesine feldspar, since the optical properties of the two that may be recognized in minute crystals, are almost identical. In coarser grained forms of chemically similar magmas the quartz appears, but the conditions attending crystallization in the contrasted cases may favor its disappearance through solid solution in one instance, and its separation as quartz crystals in the other.

In this connection it is to be pointed out that the apparent actual mineral composition of certain igneous rocks may not be the real mineral composition by as much as 30 per cent. of the whole. For the occult minerals in solid solution are as much a part of the rock as though visible. Moreover, the percentages assigned to the minerals that are seen must be in error by the amounts of the occult

minerals in solution. The problem of the determination of the mineral composition of rocks is for this reason more complex than at first appears, and is further complicated by the difficulty of determining the amounts of colored and colorless crystals, when they appreciably overlap one another in thin section.

Another obvious result of a comparison of the actual mineral composition of igneous rocks with the chemical composition of their magmas is the notable variability in the combination of minerals that may in some instances result from the crystallization of magmas of like chemical composition. This is true both as to kinds and amounts of the resulting minerals. A striking illustration of this variability is found in the mineral composition of three rocks from the same region, the parish of Gran, Norway, which have been described by Brögger. Analyses of the three are shown in columns 1, 2 and 3, Table II. The first rock is an essexite, the second a camptonite, the third a hornblendite, and while the compositions differ slightly in percentages of silica, and to a less extent in other constituents, the chemical resemblances are striking, and the three analyses lie within the range of many well-known series of analyses of particular rocks.

TABLE II.

	1.	2.	3.	4.		5.	6.
SiO ₂	43.65	40.60	37.90	42.35	orthoclase	7.2	6.1
Al ₂ O ₃	11.48	12.55	13.17	12.29	albite	—	3.7
Fe ₂ O ₃	6.32	5.47	8.83	3.89	anorthite	18.9	18.3
FeO	8.00	9.52	8.37	7.05	leucite	3.9	—
MgO	7.92	8.96	9.50	13.09	nephelite	11.1	10.2
CaO	14.00	10.80	10.75	12.49	diopside	26.9	30.2
Na ₂ O	2.28	2.54	2.35	2.74	olivine	8.0	17.9
K ₂ O	1.51	1.19	2.12	1.04	magnetite	11.6	5.6
H ₂ O	1.00	2.28	1.40	1.82	ilmenite	10.2	3.5
CO ₂	tr	2.68	— etc.	0.62	hematite	0.8	—
TiO ₂	4.00	4.20	5.30	1.82	apatite	—	2.2
P ₂ O ₅	tr	—	tr	.99	H ₂ O	1.4	1.8
	100.16	100.79	99.69	100.19	Etc.	—	0.3
						100.0	99.8

The first rock consists of lime-soda-feldspar and augite, with some olivine and mica, and rarely a little hornblende. The second rock consists of feldspar and hornblende in nearly equal proportions;

while the third is almost wholly hornblende, only 2 per cent. being pyroxene and nephelite. The same magma might have crystallized as nephelite-basanite, as appears from the calculated mineral composition shown in column 5, and from comparison with the analysis and mineral composition of a nephelite-basanite from Colfax County, N. M., shown in columns 4 and 6.

This is only an extreme case of variations well known to exist in most groups of rocks that may be referred to chemically similar magmas. And the magma already cited as capable of furnishing a pyroxene-andesite may also yield a quartz-mica-diorite, whose composition is shown in column 3 of the first table.

It is evident from these examples that the minerals called hornblende, or more properly amphibole, in the descriptions of these rocks differ widely in chemical composition, and often represent totally different mixed salts. Thus in the hornblendite of Gran, the hornblende contains all the components that might, under other conditions, have crystallized as pyroxene, olivine, feldspar, leucite, nephelite and magnetite.

Any attempt to correlate igneous rocks on the basis of the actual mineral composition, without taking into account the actual chemical composition of the minerals involved in each case must lead to confusion.

One of the most important problems in petrology is the elucidation of the laws controlling the production of mineral compounds from molten magmas. A consideration of the simpler chemical reactions that may be expected to take place in silicate solutions like rock magmas, and which do take place in crucibles in the laboratory, explains the formation of the feldspars, leucite, nephelite, quartz, diopside, hypersthene, olivine, magnetite and some other rock minerals.

Minerals like mica clearly involve the chemical action of water, or its components, hydrogen and hydroxyl, since hydrogen enters into its constitution. According to Penfield hydroxyl, and sometimes fluorine, enters into the composition of hornblendes, forming bivalent radicles with aluminium, and ferric iron. In pyrogenetic analcite, and in other possibly primary zeolites in igneous rocks, H_2O enters

into the silicate compound. The physical conditions which control the chemical equilibrium within magma solutions that yield these mineral compounds are problems for the geophysicist, though their nature may be inferred in a general way from the mode of occurrence of the rocks containing the minerals in question.

Indications of a catalytic action of H_2O within rock magmas are furnished by the association of free silica with orthosilicates containing magnesium and iron, such as the common occurrence of quartz and biotite in granitic rocks; the frequent association of quartz and tridymite with olivine in lavas; and of quartz, tridymite and fayalite in lithophysae in certain highly siliceous lavas.

The instability of these systems under changed conditions of equilibrium is shown by the inversion of hornblende to an aggregation of pyroxene, magnetite and feldspar, in some lavas; and by the solution of quartz phenocrysts in some basalts, accompanied by the formation of shells of metasilicates surrounding them.

Already laboratory research has established the range of stability of some of the rock minerals under laboratory conditions: the inversion temperatures under atmospheric pressures of the various forms of SiO_2 , quartz, tridymite, cristobalite; of the simpler compounds crystallizing as orthorhombic and monoclinic pyroxene, and the corresponding amphiboles; of a simple system involving aluminium, magnesium calcium silicates; and of other series of compounds. The value of these definite contributions to the problems of the mineral composition of igneous rocks is great. Much more is needed. And the necessity for eventually approaching nearer to the physical conditions obtaining in rock magmas is apparent, when the probable efficiency, chemical and physical, of highly heated gases under strong pressures is taken into consideration. Research under such conditions is attended with great difficulties, and some risks. Enough has been mentioned to show a wide range for future study by the geophysicist, the chemist, and the petrographer.

2. THE MATHEMATICS OF THE PETROLOGY OF IGNEOUS ROCKS.

The study of igneous rocks involves the consideration of groups of intricate relationships, the exact expression of which is at pres-

ent beyond our competence. Abstract conceptions of some of the simpler relationships, based on partial knowledge of the factors involved, serve to point the way along which quantitative investigation may be profitably pursued.

The stoichiometric character of the chemical compounds that constitute rock minerals relates them as definite functions to the chemical constituents of the liquid magma from which they crystallized. The existence of mixed crystals, and of solid solutions, introduces the treatment of series into the problem of the expression of the relationship between the mineral composition of a rock and the chemical composition of its magma. In such an expression the fixed components alone are involved. But there are definite quantitative relationships to be expressed regarding those chemical components of a magma which may act only catalytically in producing the actual mineral combination constituting the rock. Such actions may be chemical, in the sense that compounds form that subsequently disappear, as should H_2O combine with SiO_2 to form hydrogen orthosilicate, H_4SiO_4 , and subsequently resolve itself into water and quartz or tridymite. Or they may be physical, in the sense that increased molecular mobility in the magma liquid may affect the character of the crystallization by changing the freezing point and the nature of the compounds stable under the conditions obtaining at the time. In the broadest sense, then, the mineral composition of an igneous rock is a function of the chemical composition of the magma.

Since the physical conditions attending the solidification of rock magmas affect the chemical equilibrium of the constituents, as well as the physical character of the liquid, its temperature and viscosity, and also influence the chemical composition with respect to the gaseous components capable of being held in solution under pressure, the mineral composition of an igneous rock is also a function of the physical conditions attending its solidification.

To a notable extent is this also true of the texture of such rocks, their degree of crystallization, size of grain, and the shape and arrangement of the individual minerals. In the expression of these relationships the treatment of serial functions must be a pronounced feature. The gradual variations of temperature and pressure are as

essential factors in the consideration of the physical conditions of rock magmas, as the variations in texture and in mineral composition are universally characteristic features of igneous rocks.

The existence of definite quantitative relations between the mineral composition and the texture of igneous rocks on the one hand, and the chemical composition of the magma and the physical conditions attending its eruption and solidification on the other, rests on the obedience of the component elements to the laws of physical chemistry. These laws are not fully established, or known, at this time, and the relationships involved may be too intricate to be completely expressed in customary mathematical terms, nevertheless, the definiteness of the quantitative relationships can not be doubted, and approximate expressions of them become problems for petrologists of the future.

In the consideration and correlation of all known igneous rocks, variability in composition and texture and the existence of continuous series are the most conspicuous general characteristics. The variability in the composition of igneous rocks indicates heterogeneity in magma solutions. This may be inherent in them, and represent a condition of existence before the initiation of eruption; or, as is more probably the case, it may result from differentiation of homogeneous magmas during periods of eruptive activity, within more or less extended regions. Differentiation results from diffusion of compounds in solid molecules, or less complex ones, either at the time of separation as crystals, or earlier, through convection currents, differences in density, or differences in solution pressure. The resulting magma solutions differ only in the quantities of various chemical compounds; the amount of some in extreme instances reaching zero. Subsequently formed compounds are not inherently different from those in other magmas except by reason of the amounts of certain chemical components, which may be concentrated in some differentiated parts; as in the concentration of the rare elements in some pegmatites; or by different combination of chemical elements through catalytic agents. There are no inherent, or inherited, characteristics of form, organism, or immaterial traits, as in living beings. The magmas are simply differently mixed solutions of inorganic compounds.

Magma solutions possess different degrees of heterogeneity as shown by the composition of various bodies of igneous rocks. In some there are slight differences in different parts, extending through large masses. In others marked differences occur within short distances in small masses. Variability in the composition of igneous rocks from place to place is a universal characteristic, resulting in series of varieties of composition within single bodies, and among different masses. The aggregate of all such series of variations in one region may form a continuous series of wide extent; or there may be gaps in the series in one region, which may be filled by the phases of composition exhibited by rocks in another region.

In one region the composition of a nearly homogeneous rock mass of considerable magnitude may assume a certain local petrographic importance, while in another region it may appear only as a facies of another rock body. There appears to be no chemicophysical reason for the production of a magma solution of one mixed composition rather than of another very nearly the same. But it is known that magmas of intermediate, or more mixed, compositions, are more abundant than those of extreme, or simpler, compositions.

The accumulated evidence of chemical analysis, microscopical study of rock sections, and observation in the field, shows the existence of wide serial variations of composition, continuous along numerous lines, owing to the number of variable components. This evidence also shows that there is no one definitely composed magma solution more abundant throughout large areas of the earth than others; none that deserves special consideration, or may be recognized as a universal type. It is true, as already remarked, that in certain regions there are large bodies of rock having nearly uniform composition that assume local importance, and serve as types for reference in particular regions. But it must be admitted that the idea of type is subjective, inherent in the petrographer, not the rock. And when all known series of igneous rocks are treated as products of chemicophysical reactions universal in their application, the fortuitous character of the chemical composition of particular bodies of erupted magma becomes apparent, and the significance of such local types disappears in a systematic treatment of the whole body of

petrographical facts involved in a comprehensive description of igneous rocks.

Recognizing the existence of continuous series of petrographical factors, chemical, mineral and textural, necessary to the complete description and definition of igneous rocks, the problem presents itself of dividing the complex series of rocks so characterized into parts that may be described in a comprehensive and systematic manner.

A familiar example of a physical series divided in a regular manner for purposes of exact use is that of temperature, partitioned in degrees of definite proportions of a continuous scale. It is undoubtedly an arbitrary method and differs distinctly in three commonly employed usages. It might be a more "natural" method to express temperature with reference to the melting points of a series of substances; and the value of certain of these definite points as datum points is well known. But the merits of the arbitrarily, but very naturally, divided scale are attested by its universal employment.

The proposal to partition the petrographical series into quantitatively definite parts, as has been done in the Quantitative System of Classification of Igneous Rocks, the size of the divisions being arbitrarily chosen, has excited criticism by some petrographers, who consider it arbitrary, artificial and not "natural." But the objection, that measured precision condemns a classification of igneous rocks, because it makes evident "its aloofness from the scheme of nature based not on arithmetical but on physical and chemical principles,"¹ suggests a lack of appreciation of the mathematical precision of stoichiometric chemistry, and a failure to grasp the definiteness of quantitative physics, whose natural expression is found in higher mathematics. Both of these sciences are fundamental to that of petrology; and as mathematics is the language, or expression, of quantitative relationships, the more definite the knowledge of the quantitative factors and relationships obtaining in igneous rocks, the more natural will become their expression in mathematical terms.

Acknowledging the usefulness of such terms as "consanguinity" and "parent" magmas, in emphasizing the fact that there is relationship between rocks in certain instances, it must be admitted that the too frequent use of these and other biological terms, as "families"

¹ Harker, A., "The Natural History of Igneous Rocks," 1909, p. 366.

of rocks, minerals of "first and second generation," and the like, tends to convey by implication the idea that there exists among igneous rocks genetic relationships analogous to those sustained by living organisms. In fact, this idea has been clearly formulated by Harker² in stating that the mutual relationships of igneous rocks will furnish a "fundamental principle analogous with that of descent, which lies at the root of natural classification in the organic world."

The significance of the term "natural" when applied by some petrographers to petrographic classification appears to be pregnant with biological conceptions. But what is proper and natural in the treatment of assemblages of organisms is not for that reason, necessarily, proper, or natural, in the treatment of a series of chemical solutions and their solidified phases, however much the various solutions may be related to one another by reason of differential diffusion or fractional crystallization.

3. PETROGRAPHICAL PROVINCES.

Although the fact has been recognized for twenty-five years that there are regions within which the rocks erupted during any particular period exhibit certain peculiarities of mineral composition and texture that distinguish them from rocks belonging to the same general group, erupted simultaneously in other regions,³ little or no attempt has been made to define more precisely what constitutes the characteristics of any so-called petrographical province.

It has been pointed out that in some regions many of the igneous rocks are especially rich in alkalis; in some sodium being prominent; in others potassium. But nothing approaching completeness of definition, either as to composition of the rocks, or extent and limit of the region of occurrence, has ever been attempted.

And yet some very general and far-reaching speculations have been indulged in on the basis of hastily formed impressions, both as to the character of such groups of rocks and their relationship to assumed structural features of the earth. As a result certain petrographers have grouped all igneous rocks into two contrasted cate-

² *Ibid.*, p. 362.

³ Judd, J. W., *Quar. Jour. Geol. Society*, London, 1886, Vol. 42, p. 54.

gories, without considering the probability of their being many phases of combination of the variable factors of igneous rocks that must characterize all petrographical provinces of the earth.

The assumption that rocks must either belong to what have been called the "Atlantic" or the "Pacific" provinces, without serious definition of either of these rather comprehensive terms, has led to the humorous conclusion that the igneous rocks of Great Britain belonged in some periods of geological history to the "Atlantic," in others to the "Pacific" provinces; indicating the flexible, one might say caoutchouc-like, nature of these provinces.

The igneous rocks of the Andes and of the western Cordillera of North America have been referred to as representing the "Pacific" province, while the more alkalic rocks of Scandinavia and of some other parts of Europe are considered to represent the "Atlantic." The igneous rocks of Great Britain belong to neither of these distinctive groups as a whole. And the rocks erupted at different geological periods in Great Britain, while they exhibit some variations in extremes of composition, which might result from different degrees of differentiation of chemically similar magmas, bear some of those resemblances to one another that are supposed to characterize rocks of one petrographical province.

The misconception underlying the generalization responsible for the terms "Atlantic" and "Pacific," as applied to petrographical provinces, appears from the facts brought out by Cross regarding the alkalic character of some of the lavas of Hawaii, and by Lacroix regarding alkalic rocks in Tahiti; to say nothing of similar rocks in New Zealand and elsewhere in the southern Pacific. Moreover, in the midst of Europe, in Hungary, there are groups of rocks identical in all respects with those of the Great Basin in western America.

From this it is evident that one of the most important and interesting problems before petrologists is the investigation and exact definition of the districts and regions of igneous rocks in all parts of the world, with the purpose of obtaining the data with which to form definite conceptions of what have been termed petrographical provinces. Enough is known already to make it evident that there are many kinds of such groups of igneous eruptions and not two strongly contrasted series; that they blend into one another in composition;

that the delimitation of the regions, or provinces, may be pronounced in some instances, and ill-defined in others.

The character of the rocks in different provinces, and the distribution of provinces throughout the earth, together with their relations to the geological structure and dynamical history of the region in which they occur, furnish problems of the first magnitude in petrology.

One of the questions to be answered is: the relation of the composition of igneous rocks of different parts of the earth to its isostasy. The configuration of the earth's surface demands the presence of material of different densities beneath the surface. Does this show itself in the character of the material erupted in different regions. An answer to this can not be given offhand. The requirements in density are relatively so slight when great volumes are concerned, as pointed out recently by Hayford;⁴ the series of igneous magmas of any region is so diversified in composition and density; and the estimation of their several volumes is so hazardous an undertaking that a reasonable solution of the problem can only be expected after the accumulation of a great amount of exact data.

Whether there is any relation between the kinds of magma erupted in a particular region and the dynamical events within the region is another problem yet to be solved. Assertions to the effect that there is a definite relationship have been made, but they are in the nature of broad generalizations upon questionable premises, producing the results already discussed in connection with the terms "Atlantic" and "Pacific."

It is possible that differences in the sequence of dynamic events in various regions, or in one region at various periods of its history, may be accompanied by differences in the processes and results of differentiation of chemically similar magmas; that is, in series of erupted rocks, but the existence of such relationships has yet to be clearly established. For it is also possible that the material of the earth may be heterogeneous in composition, differing somewhat from place to place, and yielding different kinds of magmas in different

⁴ Hayford, J. F., "The Relations of Isostasy to Geodesy, Geophysics and Geology," *Science*, N. S., Vol. 33, No. 841, 1911, pp. 199-208.

regions, each of which may undergo local differentiation according to conditions of its eruption. The apparent persistency of the major features of relief on the earth's surface and the demands of isostasy suggest an absence of homogeneity within the material of which it is composed. The solution of these fundamental problems in geology must rest on petrological research along the lines here indicated.

Such are some of the more obvious problems of petrology, the solution of which involves the coöperation of petrographers with the chemist, the geophysicist and the geologist.